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# Safety Considerations for the Design of Modern Elevator Systems

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# **SAFETY CONSIDERATIONS FOR THE DESIGN OF MODERN ELEVATOR SYSTEMS**

by  
Abhijaya Shrestha

A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of  
the requirements of Sally McDonnell Barksdale Honors College.

Oxford  
May 2019

Approved by

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## **DEDICATION**

To my grandmother, Mrs. Lata Giri

## **ACKNOWLEDGEMENTS**

I would like to thank Dr. Tejas Pandya for his advice, mentorship, assistance and continued support while working on this article. I would also like to thank Dr. Jagdish Sharma and Dr. Arunachalam ‘Raj’ Rajendran for being my readers and helping me get to this final draft. In addition, I am indebted to ThyssenKrupp Elevator Manufacturing in Middleton, Tennessee and the Director of Manufacturing, Mr. Kevin Perkins, for giving me an opportunity to be a Manufacturing Engineering Co-op at the plant – the experience was very fulfilling and taught me most of the things I learned and wrote in this report.

I could not have completed this work without the information provided by Mr. Lubomir Janovsky, Mr. George R. Strakosch, United States Transportation Research Board and all other sources cited in this paper. Special thanks go to Mr. Amrit Poudel and Ms. Claire Cozadd for helping me proofread and edit this final draft.

## **ABSTRACT**

The main purpose of this work is to perform an analysis on elevator safety considerations in the United States. This report introduces the development of elevators through its history, definitions and commonly used concepts in the elevator industry. Elevators are already an important part of day-to-day life for thousands of people and have significant role to play in the future of urbanization due to increasing population density and decreasing real estate. Elevators not only make vertical transportation convenient, but also play an important role in providing accessibility for people with disabilities; so, its safe and reliable operation is very crucial. Elevator maintenance and safety practices around the country are evaluated in this article and a study on various elevator related accidents was performed to recommend safety practices. Modern elevators are very safe in general, but poorly maintained systems, passenger safety vulnerabilities, incomprehensive work instructions, negligence and lack of proper safety protocols still cause several accidents every year. The engineering parameters related to elevator safety such as rated load, rated velocity, brakes and safety gears are also explored, and a brief study is done on linear induction motor elevators through ThyssenKrupp Elevator's MULTI. Ropeless elevators that can move both vertically and sideways are essential in developing mini-cities within large buildings and architectures, so it is important for safety code regulation agencies to keep up with time and technology, while innovators must prove the reliability, safety and applicability of new technologies.

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# 1. INTRODUCTION

Elevators are traditionally seen as a medium of vertical transportation. Lubomir Janovsky, in his book *Elevator Mechanical Design* defines an elevator as: “a permanent lifting equipment serving two or more landing levels, including a car for transportation of passengers and/or other loads, running at least partially between rigid guides either vertical or inclined by less than 15 degrees” [1].

Today, there are prototype elevators around the world that move horizontally as well as vertically. Even though most of them are not manufactured commercially, mostly due to the shortcomings in meeting certain safety regulations around the world, recent technological developments have allowed engineers to expand on the definition of elevators. For instance, ThyssenKrupp recently developed a new rope-less elevator system known as MULTI, which moves vertically as well as sideways [2].

The best way to avoid confusion in defining an elevator for literary purposes is by referring to the definition given by Occupational Safety and Health Administration (OSHA), at least in the United States, since no elevators can be manufactured commercially without meeting their safety regulations. According to OSHA Code of Federal Regulations (CFR) 1917.116(a):

“Elevator” means a permanent hoisting and lowering mechanism with a car or, platform moving vertically in guides and serving two or more floors of a structure. The term excludes such devices as conveyors, tiering or piling machines, material hoists, skip or furnace hoists, wharf ramps, lift bridges, car lifts and dumpers [3].

Elevators are undoubtedly going to be a big part in the future of technology and urbanization. In big cities like New York and Hong Kong, the scarcity of real estate land for an increasing population density is already evident, and it demonstrates that the buildings in the future will likely rise vertically more than it will spread horizontally. As a result, elevators as transportation will be just as integral part of the society in the future as automobiles are today. This also means that the design, manufacturing and maintenance of elevators need vigorous engineering as we attempt to uphold the safety standards for a rapidly developing technology.

Even though elevators are a part of day-to-day life for most people in United States, there is not a lot of information available, especially due to lack of proper documentation and agencies’ hesitancy, to release information about how they work and how to make sure their safety is not compromised. Elevator breakdowns and damages are still very common, and even though serious casualties are rare, elevator accidents can be scary and reminiscent of how crucial its safety and maintenance are. Modern technology has made elevators very safe but there are still old buildings that have old elevators that need to stay operational. The maintenance and manufacturing of parts for these old elevators still need to be continued while we transition to modern elevators. This makes it critical for

various agencies to have articles and documentations of design specifications and maintenance standards for elevators over time.

### *1.1. History and Design Development of Elevators*

The earliest forms of elevators were manually driven windlasses, animal-powered hoists, shaft ways seen in ancient Roman ruins and other vertical movement systems based on the simple machine - pulley. One could even argue that elevators were discovered when pulleys were. In mountainous landscapes like of Tibet, baskets drawn by pulley and rope are still used to vertically transport people, driven by a windlass and manpower [4].

Steam driven hoists were mostly used for material transportation in the early 19th century and disastrous when used for people since the rope was made of fiber and there was no fail-safe mechanism in case the rope broke [4].

The definition of modern elevators more or less includes a mechanism to prevent the carriage from falling in the event the linkage or lifting means fail. Elisha Graves Otis invented such elevator safety device in 1853 when working in a factory and wondering how he could clean up better by moving the old debris to the upper levels of the factory. His safety device operated by causing a pair of spring-loaded dogs to engage the cog design of the guide rails when the tension of the hoisting rope was released [4, 5].

Despite the improved safety of elevators, it was not until 1857 that public started to accept and order elevators for passenger use. That was the year when the first elevator

was installed in the store of E.V. Haughwout & Co. in New York. This elevator traveled five floors at the then breathtaking speed of 40 feet per minute (fpm) [4].



*Figure 1: Beginnings of Elevators [5]*

**Source(s):** Elevators Market, *The Essentials of Elevatoring: Elevators History*, [Online], 10 June 2018, Available: <https://elevatorsmarket.com/the-essentials-of-elevatoring/>, Accessed: 4 February 2019.

Over the next few years, improved wire rope became more readily available and there were rapid advances made in steam motive power for hoisting. The public and architectural designs started to see more acceptance and approvals, and this revolution in elevator industry sparked an unprecedented demand for “downtown” space, the result of which we see skyscraper cities such as Manhattan, Hong Kong and Dubai [4].

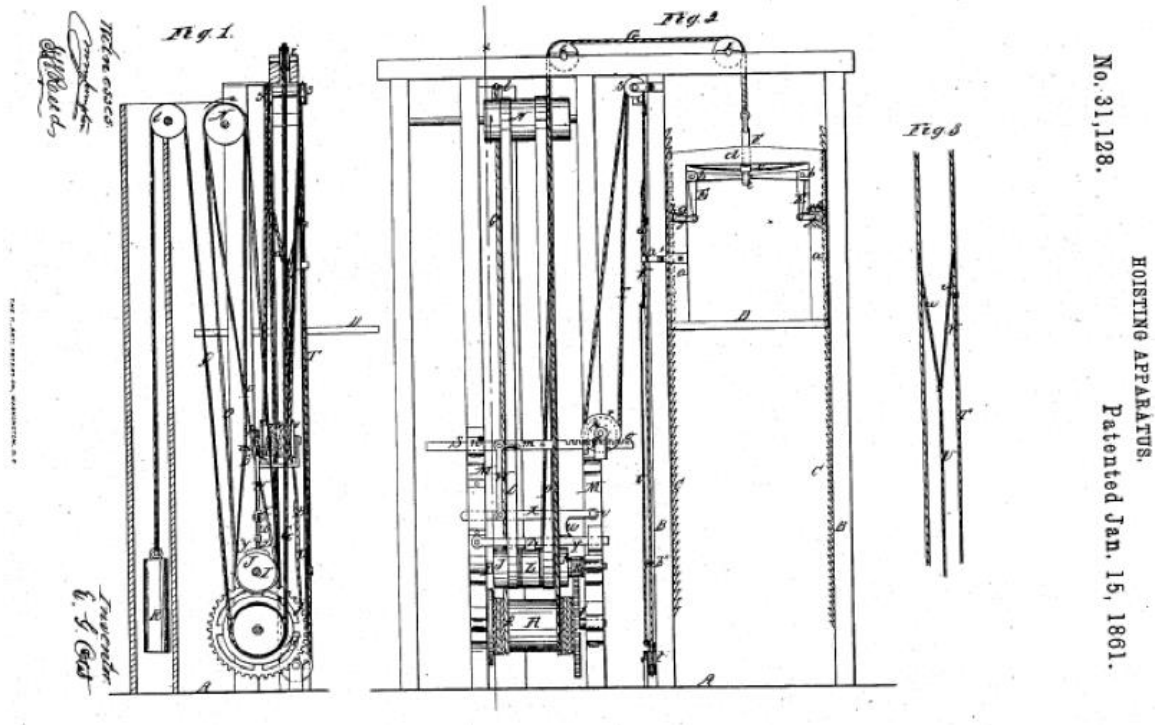


Figure 2: Patent 31128 "Elevator" Otis' Patent drawing of the safety stop [6]

**Source(s):** D. Salmon, IP.Com, *Looking Forward, Backwards, and Sideways: A Patent History of Elevators*, [Online], 27 Nov 2017, Available: <https://ip.com/blog/looking-forward-backwards-sideways-patent-history-elevators/>, Accessed 4 February 2019.

Those cities did not show a big vertical growth in their present form until the 1870s however because the elevator mechanism was still a slow cog, almost like a vertical steam-driven railway. This was until the hydraulic elevator started hitting the market with its ease of access and egress which was not limited by winding drums anymore. The hydraulic elevator kept advancing on its technology as it moved from direct ram drive to roped or geared hydraulic drive, making it capable to work in buildings more than 30 stories tall. Most elevators in 1880 to 1900 era had hydraulic elevators [5, 6].

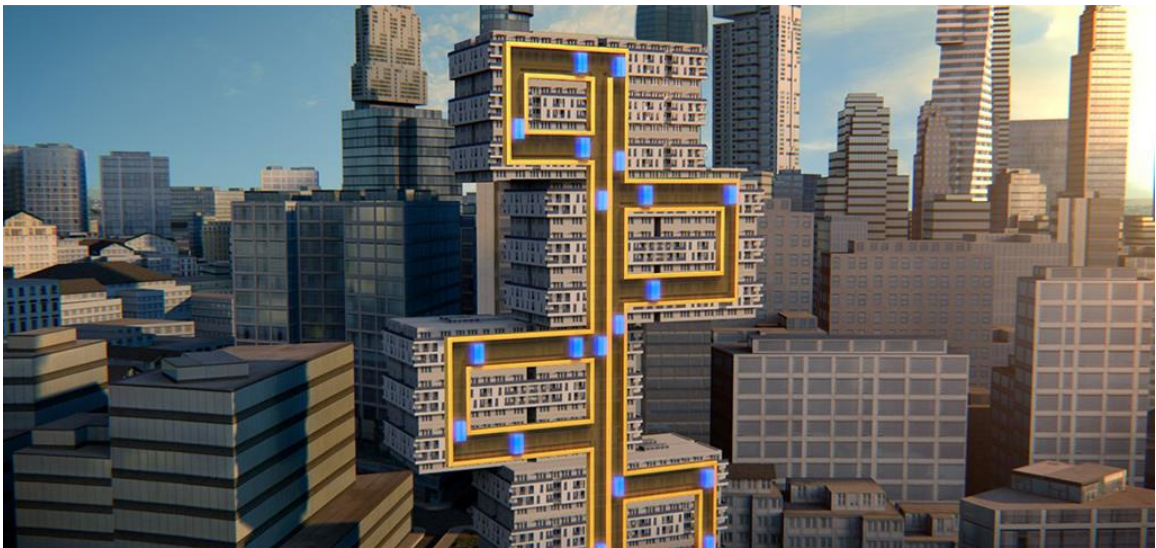
The Demarest Building of New York installed the first electric elevator in 1889, which was very similar in design to the earlier steam-driven drum elevator, except the steam engine was replaced with an electric motor. As buildings started to get taller and taller, and electricity became more common in the early 1900s, the roped hydraulic could not meet the elevating needs, and the traction elevator was first introduced commercially in 1903 [4].

A traction elevator transmits the lifting force to the hoist ropes by friction between the grooves in the machine drive sheave and hoist ropes. The ropes wrap over the machine drive sheave in grooves and connect the carriage with the counterweight. It is ensured that the ropes sit in the groove due to the weight of the car and counterweight. The traction elevator eliminates the drawbacks of drum and hydraulic machines and are what made the skyscrapers of 100 or more floors possible. Today, there are different types of traction elevators and modern hydraulic elevators in use around the world that is contributing to urbanization by allowing efficient transportation in tall buildings.

As we can see from its history, elevator is a technology in a constantly evolving industry, where changes in technology, modern building codes, demands of the marketplace and innovation in technology happen constantly. In 2003, ThyssenKrupp Elevators unveiled the twin elevators where two cars would operate in a single shaft for the first time. The upper car could travel between all the floors except the lowest and the lower car could travel between all the floors except the highest. Using computer programming to direct cars in order to efficiently flow traffic in tall buildings, this was a revolution in elevator

industry since it greatly reduced wait times in high-traffic and high-rise buildings. Even though the twin elevators have been operational in several parts of Europe, Asia and Australia for several years, it never really saw widespread market in the United States until recently when Georgia Tech University made an order from ThyssenKrupp Elevators Americas in 2016.

In the last five years or so, ThyssenKrupp has been taking this technology to the next level by introducing MULTI. MULTI incorporates multiple cars in the same shaft (hence the name MULTI) and integrates the direct drive as the part of the hoistway gap by eliminating ropes. The linear technology enables the car to move both vertically and sideways. This technology is very similar to the one used by Japan's bullet trains [2].



*Figure 3: MULTI by Thyssenkrupp [2]*

**Source(s):** Thyssenkrupp Elevator AG, MULTI, [Online], Available: <https://multi.thyssenkrupp-elevator.com/>, Accessed: 15 March 2019.

## *1.2. Classification of Elevators*

Even though elevators can be classified based on various characteristics, the design principles and manufacturing of components depend on the drive method utilized. There are three types of elevators based on its drive method [1].

1. Electric elevators
2. Hydraulic elevators
3. Pneumatic elevators

### 1.2.1. Electric Elevators

Electric elevators can be further classified into three types [1]:

- A. Traction drive (geared or gearless)
- B. Positive drive or drum drive
- C. Linear Induction Motor (LIM) drive

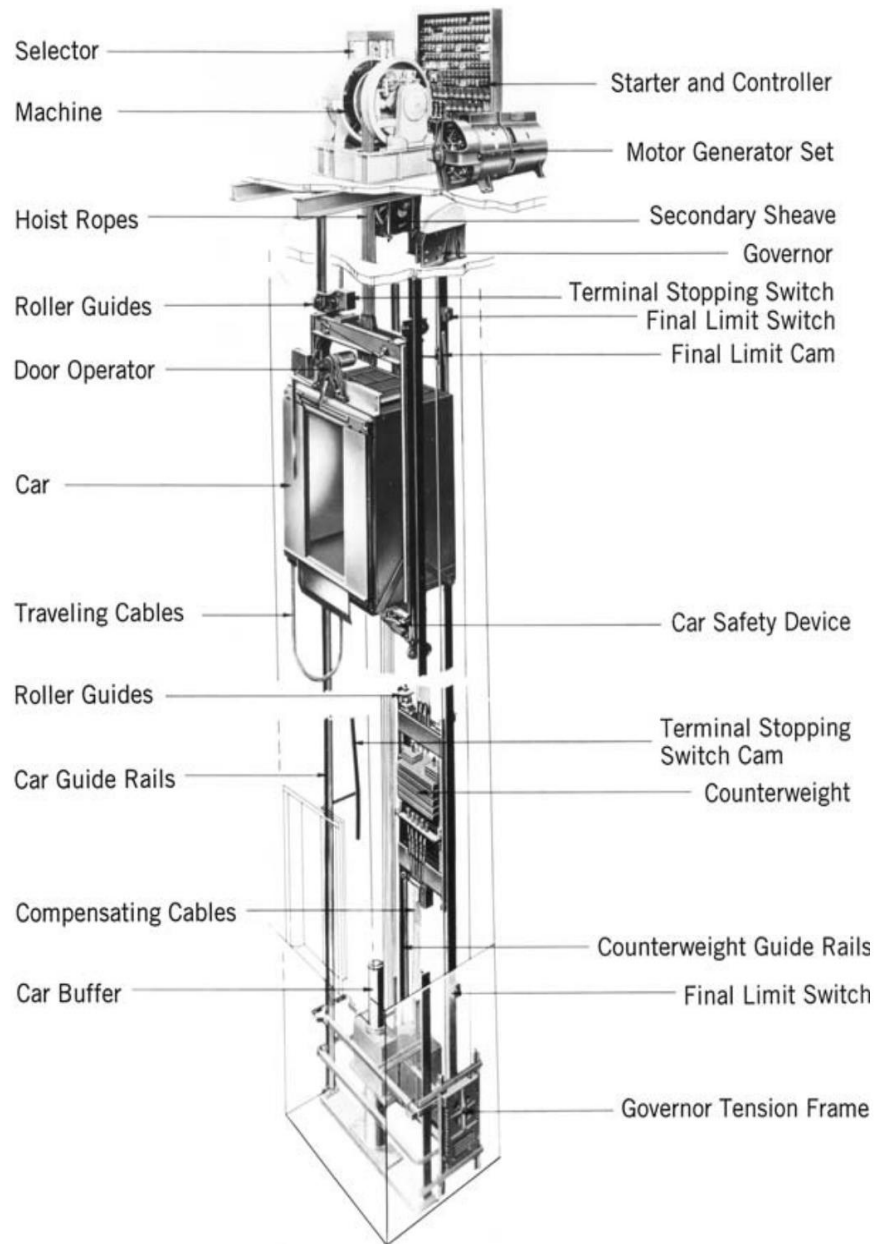
Traction elevators use ropes that pass over a wheel and lift the car by using an electric motor placed on the top of the hoistway. A counterweight is used to offset the weight of the car (and passengers) so that the work to be done by the motor is reduced, resulting in a more efficient elevator operation.

Traction elevators can further be classified into geared and gearless traction elevators.

The motor in a geared elevator is connected to a gearbox which drives the wheel while in a gearless elevator, the wheel is attached directly to the motor. Geared elevators typically

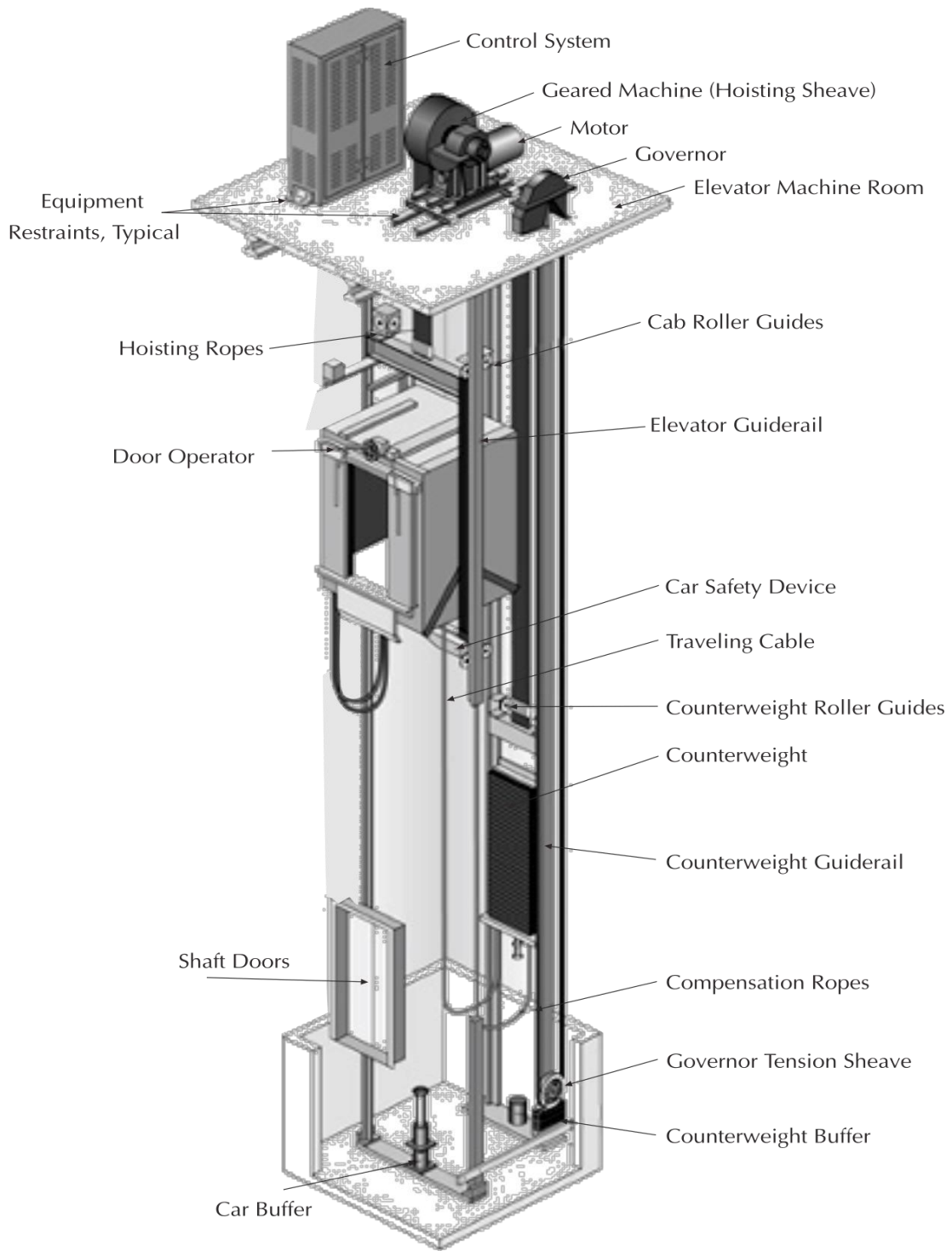


fail to reach speeds and heights that gearless elevators can, and therefore, most high-rise buildings are equipped with gearless traction elevators [7].



*Figure 4: Gearless Traction Elevator [4]*

**Source(s):** G.R. Strakosch, Courtesy of Otis Elevator, *The Vertical Transportation Handbook*, 3rd ed. John Wiley & Sons, Inc., 1998.



*Figure 5: Geared Traction Elevators [8]*

**Source(s):** Star-way elevators, *Traction Elevators*, [Online], Available: <http://starwayelevators.com/traction.php>, Accessed: 4 February 2019.

Traction elevators may or may not have a machine room. Machine room's presence is more common in the United States because of building codes in many places that doesn't allow the drive system to be in the hoistway. These building codes are slowly being updated to allow machine-room-less traction elevator that have an override space accessible from the top of car. Even if the machine room is not present, there is a control room on the top floor and within 150 feet of the machine that houses the control boxes. Machine-room-less elevators are a good choice for mid-rise buildings since they save space and energy with similar operation and reliability of a traction elevator with a machine room. A representative diagram comparing machine-room traction elevator, machine-room-less traction elevator and a typical hydraulic elevator has been shown in Figure 7 [7].

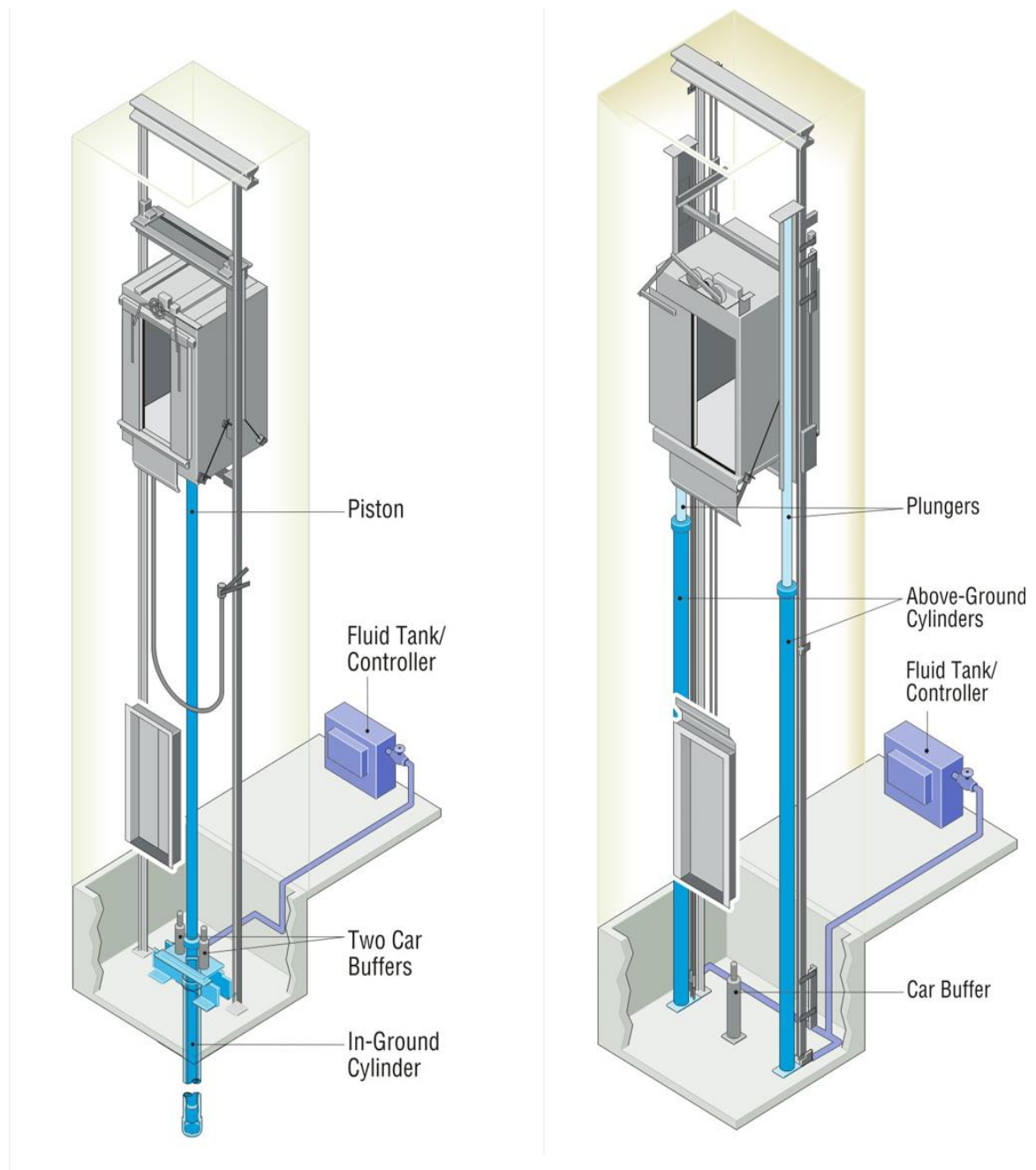
A positive drive elevator also has chain or rope suspensions, but the drive method does not work due to friction. An example is the drum drive elevators where rolling steel ropes attached to the drum winds around the drum to move the elevator carriage. These were the earlier forms of elevators that are not in use anymore, except for some low-rise freight elevators. Due to several incidents of final limit switch fails, these can be considered the most unsafe type of elevators [9].

While winding drum elevators are the things of the past, Linear Induction Motor (LIM) drive is widely considered the elevators of the future. In LIM drive, the linear motor produces the driving force that acts readily upon the carriage (or the counterweight).

Since no transformation mechanism is required, the reliability and efficiency of the system is increased without the need for a machine room. There have been several design prototypes of linear induction motor drive elevator systems produced by different companies over the last few decades. LIM drive elevators could be roped or ropeless with some form of magnetic levitation [1].

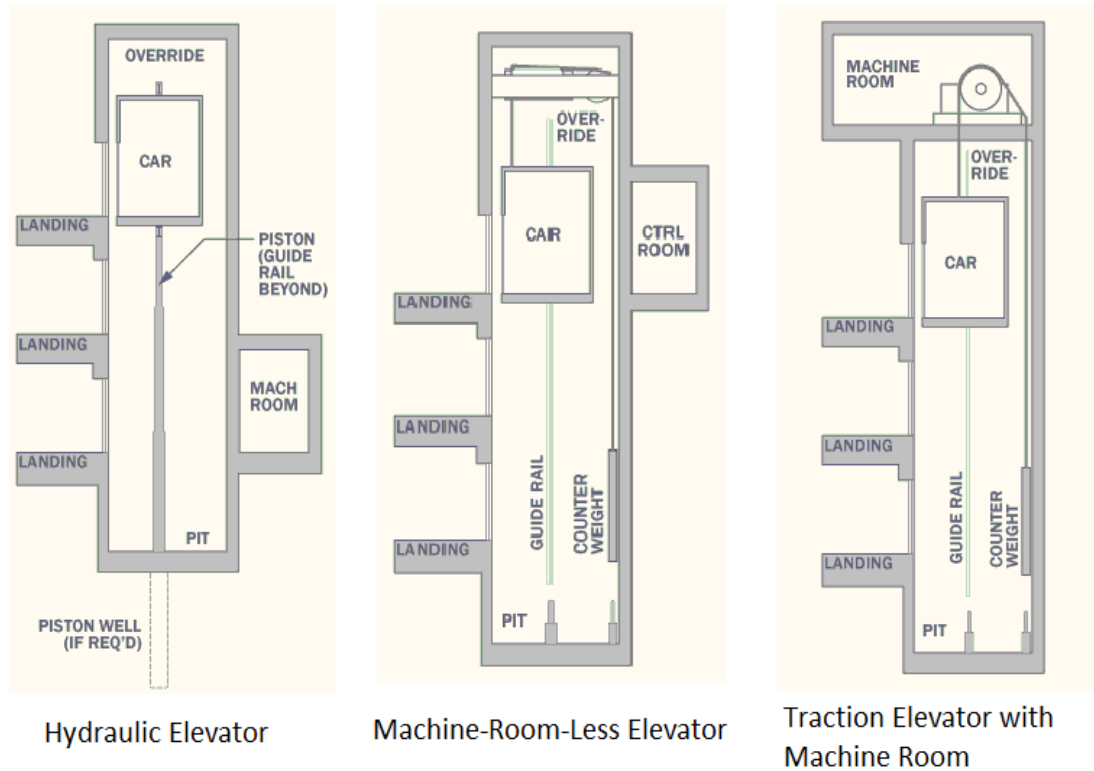
#### 1.2.2. Hydraulic Elevators

Hydraulic elevators are plunger-driven with a piston below the elevator that pushes the car up. An electric motor is used to force oil (hydraulic fluid) into the piston. Unlike traction elevators, the machine room is located on the lowest floor next to the elevator shaft. Traditionally, the hydraulic elevators have a sheave that extends below the floor of the pit but hole-less and roped hydraulic elevators are being more popular in the last few decades. Telescoping pistons are used in many of these to accommodate the hydraulic system without or with a shallow hole below the floor of the elevator pit. Hydraulic elevators are usually cheaper to install and maintain but are not favorable for high-rise buildings [7].



*Figure 6: Hydraulic Elevators (Hole and Hole-less Types)[10]*

**Source(s):** Express Lifts Limited, *Hydraulic Lifts*, [Online], Available: <http://www.expresslift.co.in/hydraulic.html>, Accessed: 4 February 2019.



*Figure 7: Hydraulic versus traction elevator comparison [7]*

**Source(s):** Archtoolbox, *Elevator Types*, [Online] Available: <https://www.archtoolbox.com/materials-systems/vertical-circulation/elevatortypes.html>, Accessed: 17 February 2019.

### 1.2.3. Pneumatic Elevator

A pneumatic or vacuum elevator works by utilizing air suction to move the carriage up or down as a result of difference in air pressures above and under the carriage. Turbines are used to operate as exhausts on top of the elevator. Pneumatic elevators are generally used inside residential houses of a couple floors [11].

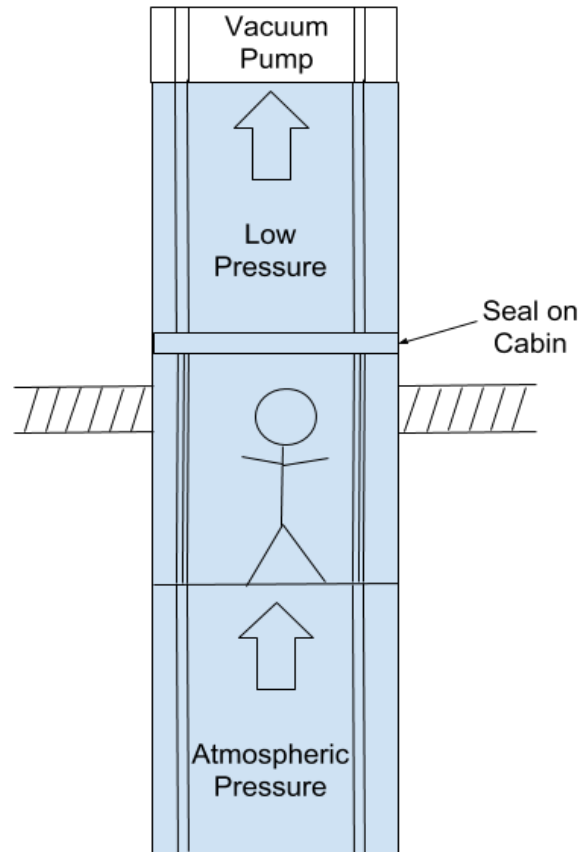


*Figure 8: A Pneumatic Elevator [11]*

**Source(s):** Pneumatic Vacuum Elevators, LLC., *Principles and Components*, [Online], Available: <https://www.vacumelevators.com/principles-components/>, Accessed 17 February 2019.

There are several other kinds of elevators developed by various companies that have not been commercialized yet due to their respective limitations, mostly due to failure in meeting the present safety codes, but have utilized creative technological design methods and could potentially be a part of the future of vertical transportation. SchindlerMobile ®

by Schindler Elevators and MULTI by ThyssenKrupp Elevators are some notable examples.



*Figure 9: Pneumatic Elevator Schematic*

### *1.3. Frequently used electric elevator parts:*

In order to dig deeper into the specifics about an elevator, it is important to understand common elevator components. While there are numerous components in any given elevator, and there are several different types of elevators, the main parts of an electric elevator are discussed here.



1. Elevator machine
2. Car
3. Suspension ropes
4. Counterweight
5. Car guide rails
6. Counterweight guide rails
7. Car buffer
8. Counterweight buffer
9. Controller
10. Selector
11. Selector driving tape
12. Overspeed governor
13. Governor tension pulley
14. Travelling cable
15. Door operator
16. Roller guide
17. Car safety gear
18. Car door safety edge
19. Diverting pulley
20. Safety limit switch
21. Final limit switch

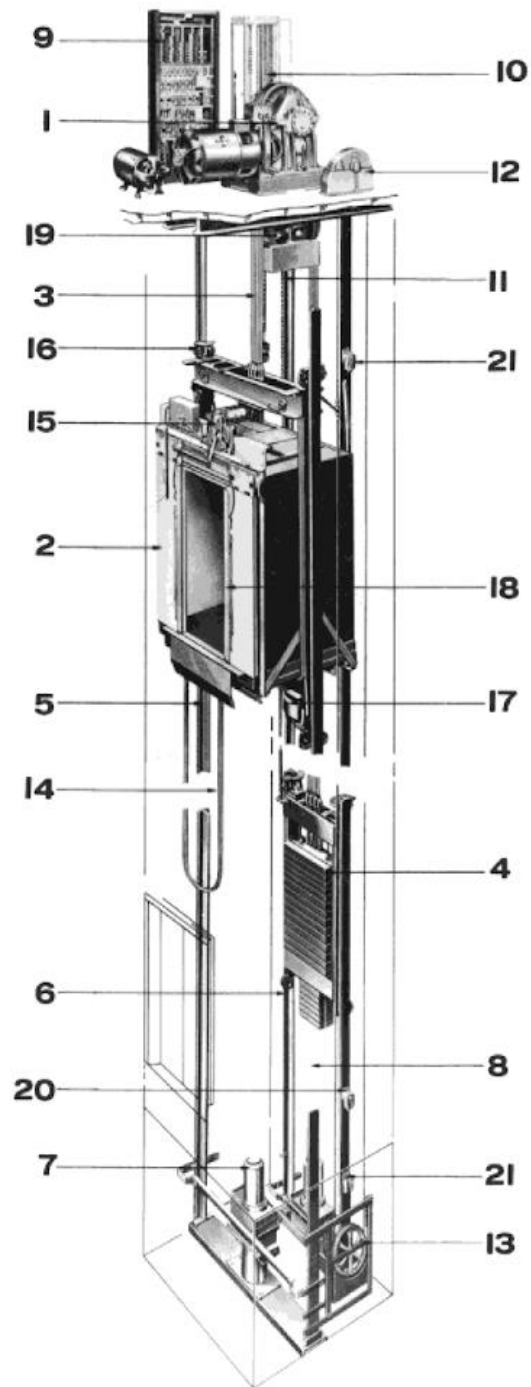


Figure 10: A typical passenger elevator (Picture courtesy of Otis Elevator)[1]

**Source(s):** L. Janovsky, *Elevator Mechanical Design*, Picture Courtesy of Otis Elevator, 2nd ed. Ellis Horwood Limited, 1993.

### 1. Suspension

Suspension refers to the steel wire ropes or chains used to suspend cars and counterweights. Since this is what hangs the carriage, proper selection, life, maintenance and replacement of suspension ropes are critical to maintaining safety. The factor of safety when selecting suspension ropes can be calculated based on rated load, mass of the car and the counterweight, height of travel, rated speed, roping factor and whether or not compensating cables are employed [1].

Factor of safety is given by,

$$f = \frac{\text{minimum breaking load of the rope}}{\text{maximum static force in the rope}} = \frac{n \times N}{F}$$

where, n is the number of ropes, N is the minimum breaking load of one rope and F is the maximum tensile force in the elevator ropes. It is calculated with the stationary carriage on the lowest floor with the rated load [1].

### 2. Driving machine

The drive machine is a general term that is used to refer to the driving mechanism of an elevator. For instance, in a traction elevator, it would mean the power unit that comprises of electric motor, gears, brake, sheave, drum or chain sprockets, etc.

### 3. Car

Car is short for carriage and refers to the part that most passengers experience. The carriage is what carries passengers and/or other loads. In technical terms, it refers to the overall framework that consists of the sling, metal framework connecting to the

suspension, the platform floor along with the car enclosure. The suspension gear, guide rails, safety gear, car door and door operator are also attached to the car.

#### 4. Counterweight

The counterweight balances the weight of the car and the load in an elevator. The counterweight is tipped off in the desired direction to move the car between floors. This also helps to reduce the work done by the motor.

#### 5. Hoist way or Elevator Well

It is the tubular space, extending from the pit floor to the roof, where the elevator is set up and car travels. The space is usually enclosed and consists of the car, counterweight, guide rails, buffers, landing doors, etc.

#### 6. Safety gear

In case the suspension fails, the safety gear is the mechanical device built as a fail-safe for stopping the car and/or counterweight, and holding it in that location. Along with the overspeed governor, the safety gear also functions when the speed of the elevator car exceeds the rated value.

#### 7. Buffers

Buffers are placed at the bottom of the hoistway, beyond the lowest point where car and counterweight are normally supposed to travel, to accumulate or dissipate the kinetic

energy of the car and counterweight. They could be of several different types such as spring type, oil type, polyurethane type, etc.

#### 8. Electrical components

There are several different electrical components used in an elevator such as for lighting, safety features, displays, digital door operators, etc. including electric safety.

#### 9. Control systems

The control systems, usually located in the control room or the machine room if any, is a processing unit to perform diagnostics, analyze traffic, and control the elevator functionality in general. For instance, the 32-bit microprocessor controller can make more than thousands of decisions per second.

#### 10. Door Operator

This part of the elevator controls the opening and closing of the door when reaching destination floors. They are usually equipped with a sensor in modern elevators to avoid trapping of people and objects in between the door, and they should only open when the car is stationary on a particular floor. It is estimated that a typical door operator works about 1.75 million times in 10 years. About 80% of all elevator problems are related to door operators, and several elevator related accidents have been associated with them. Therefore, it is important that they are properly maintained over time. The modern digital door operators are much safer than the traditional ones.

## **2. ENGINEERING AN ELEVATOR**

### *2.1. Technical Parameters*

The main technical terms of concern when designing and manufacturing an elevator are:

1. Rated Load (Q): The load that the elevator is designed to carry at its rated speed.  
According to ASME A17.1, 2.16.8., an elevator should safely lower, stop and hold an additional 25% in excess of the rated load. The term '125% of rated load' is seen being used throughout the ASME safety code booklet [12].
2. Rated Speed (v): The maximum speed in upward direction at which an elevator is designed to operate with the rated load.
3. height of travel
4. number and location of stops
5. dimensions of elevator well, car and machine room
6. Load factor or duty rating, voltage of main supply
7. Control system and operator type
8. Landing and car doors arrangement
9. Number of elevators in a building and their locations
10. Environmental conditions if relevant

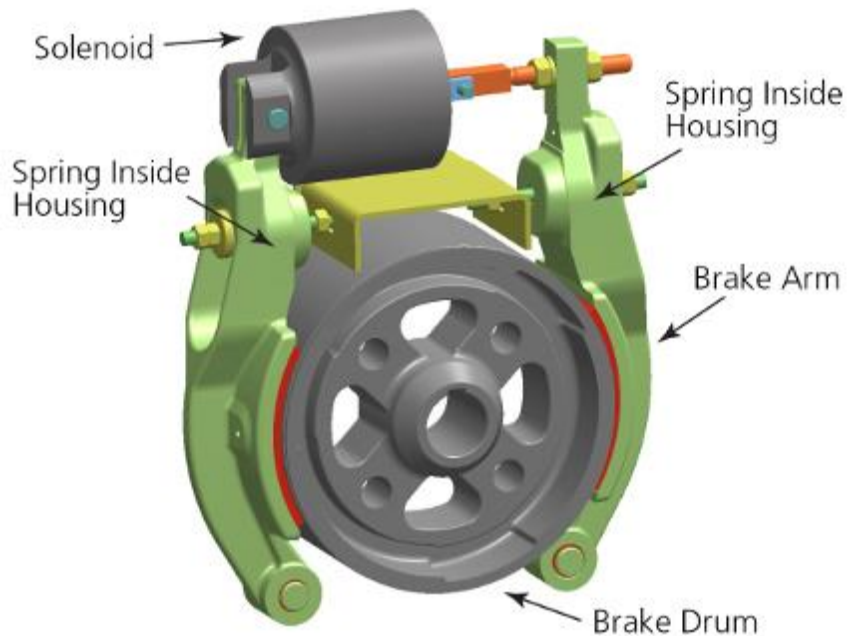
Most of these parameters are given by the manufacturer based on customer needs, building conditions and requirements, and the elevator design. Only with these parameters in consideration along with safety codes and regulations, elevators are designed, manufactured and installed. Due to the diverse nature and different needs of elevators for every other building, most elevators except for standard government building and transits are made to order. So, each elevator is designed independently, and different components are manufactured separately and then installed in location. That is why, assembly lines in an elevator manufacturing plant are not as common. This also makes elevator maintenance a specialized job since elevators can be different from building to building. While every part of the elevator plays a significant role, the most critical components in engineering a safe elevator are its brakes, safety gears, suspension cables, buffers and door operators.

## *2.2. Brakes*

Brakes are the components of biggest safety concerns when designing an elevator for obvious reasons. The braking system of elevators are not just required to stop the carriage at desired floors but must also operate automatically if there is a power outage or loss of power supply to control circuits. There should be at least two independent electric devices to control the interruption of electric current, and brake should operate as the electric circuit is interrupted (ASME A-17, 5.3.1.17.1. (c)(2)) [12]. Therefore, all elevators in use must be equipped with an electromechanical friction brake which should be able to stop the elevator carriage with up to 125% of rated load travelling at its rated

speed. The brake should not only stop the carriage but also hold the system at rest afterwards. This retardation should not be more than what results from the fail-safe braking system of safety gears or buffers [12].

Elevator brakes are usually drum or disc type; band brakes are not allowed in elevators. A typical electromagnetic drum brake has a spring assembly, two brake arms with linings and a magnet assembly. When the solenoids are de-energized, the brake drums are gripped by the brake arms under the influence of compression springs, inducing the braking torque. The brake linings are made of material with high coefficient of friction and have dimensions that reduce specific pressure (and decrease wear) [1].



*Figure 11: A typical DC brake's CAD geometry [13]*

**Source(s):** S. Brown, N. Elabbasi and M. Hancock, Veryst Engineering, Design Fax, *Simulation solves mystery behind elevator accident*, [Online], May 2015, Available: <http://www.designfax.net/cms/dfx/opens/article-view-dfx.php?nid=4&bid=456&aid=3901&et=featurearticle&pn=02>, Accessed: 15 March 2019.

The following equations are adapted from *Elevator Mechanical Design*, 2<sup>nd</sup> ed., by Lubomir Janovksy and are utilized in choosing the right type of braking mechanism for an elevator system [1].

$$\text{Static Torque } (M_{st}) = 1/i (1.25Q + K - Z + m_L i) \times g_n \times D / (2i_G) \times \eta_2$$

Where, Q = rated load

K = mass of the car

Z = mass of the counterweight

i = roping factor

m<sub>L</sub> = mass of one fall of suspension ropes

g<sub>n</sub> = acceleration of free fall

D = sheave diameter

i<sub>G</sub> = gear ratio

η<sub>2</sub> = mechanical efficiency of the system related to the conditions of braking

$$\eta_2 = \eta_{RS} \times \eta_s \times \eta_G'$$

where

η<sub>RS</sub> = efficiency of the roping system

η<sub>s</sub> = efficiency of the sheave

η<sub>G</sub>' = efficiency of mechanical gearing between the motor and the sheave for reversed power transmission



The direction of power transmission should be considered carefully, especially with worm gearing application.

$$\text{Dynamic Torque } (M_i) = I \times \epsilon$$

Where,

$I$  = moment of inertia of all moving parts of the system related to high-speed shaft

$\epsilon$  = angular retardation of the high-speed shaft

$$\text{Total moment of inertia } (I) = I_1 + I_2 + I_3$$

Where,

$I_1$  = moment of inertia of the rotor, brake drum and worm

$I_2$  = moment of inertia of the worm wheel and sheave

$I_3$  = moment of inertia of all parts of the system which are in linear motion

It should be noted that these values are based on the moment of inertia related to high-speed shaft, which could be different from the moment of inertia related to their axis of rotation. However, if one is known, it can be easily translated to another based on the conservation of kinetic energy. For instance, if moment of inertia of worm wheel and sheave related to their axis of rotation ( $I_2$ ) is known, it can be translated to the high-speed shaft as:

$$I_2 = I_2' \times \eta_G' / i_G^2$$

Likewise, for  $I_3$ ,

$$I_3 = {}^1I_3 \times \eta_G' / i_G^2$$

The moment of inertia related to low speed shaft (  ${}^1I_3$  ) is given by,

$${}^{1/2} {}^1I_3 \omega^2 = {}^{1/2} [(1.25Q + K + Z) \times v^2 + m_L \times (i \times v)^2] \times \eta_{RS} \times \eta_s$$

where  $\omega$  = angular velocity of the low speed shaft and is given by,

$$\omega = 2i v/D$$

here,  $v$  is the levelling speed of the counterweight.

Putting the above equations together, we get,

$$I_3 = (1.25Q + K + Z + m_L \times i^2) \times \frac{D^2}{4i^2 \times i_G^2} \times \eta_2$$

Due to the friction brake, the braking force is constant with uniform retardation. The angular retardation ( $\epsilon$ ) is given by,

$$\epsilon = \frac{\pi \times n_2}{30 t_b}$$

where  $n_2$  = revolutions per minute of the motion when the brake is initially applied

and  $t_b$  = braking time

The braking torque needed for safely operating an elevator can be determined as:

$$M_b = M_{st} + M_i$$

We may use simple kinematic equations for uniform retardation in order to make estimations regarding the braking time specifications.

$$t_b = 2l/v = v/a$$

where  $l$  = distance between the car and the destination floor when brake is operated,  $v$  = initial velocity of car and  $a$  = rate of retardation

Even though it may be tempting to set a high rate of retardation to lower the braking time, it might create excessive braking torque at high landing positions since the static torque will be a factor.

$$M_b = -M_{st} + M_i$$

It is often a practice in elevator manufacturing that after the brake has been selected, the rate of retardation is calculated for the case of car stopping at highest landing. This is a check to ensure that the braking torque is not too high to create discomfort for passengers.

When selecting a brake, the thermal capacity of the brake and the drum may also need an analysis along with the braking torque applied to the drum. This is because all the moving elevator parts will dissipate heat over longer use. The heat generated between the drum and the brake shoes per hour due to friction can be given by,

$$A = M_b \times \omega_a \times t_b \times z$$

Where,  $\omega_a$  = average angular velocity during braking time =  $\frac{\pi \times n}{60}$

$n$  = revolutions per minute of motor when braking action starts

$t_b$  = average braking time

$z$  = number of operations per hour

Since there is never a set number of operations per hour (z), an estimation of peak usage needs to be done. In most elevators, this is usually low enough that the analysis is not required but it will be needed if there are many large moving parts involved, levelling speed is high, or the number of operations is relatively large. The number of operations is specified in the elevator manufacturer's catalogue along with the braking torque.

The braking system is very important to design a safe elevator and therefore, after selecting a brake, it is important to have it undergo a series of tests. Several iterations of the test is performed to make sure that the brake produces the desired braking torque. This test is repeated under different conditions of load factors, number of operations per hour, temperatures, etc. The brake linings should also not have excessive damage after long term use.

The testing is usually done in a testing bench where a driving motor accelerates a flywheel to a certain angular velocity, on which the brake is operated. A programming device is used to alter and adjust different operating conditions.

Considering the rated load plus an extra 25%, the braking torque for stopping at the lowest landing level can be given by,

$$M_b = M_{st} + M_i = M_{st} + I \times \epsilon$$

which can also be expressed in terms of the moment of inertia of all movable masses of the bench ( $I_1$ )

$$M_b = I_1 \times \epsilon$$

Therefore, combining the above equations,

$$I_1 = I + M_{st}/\epsilon$$

We can now deduct the moment of inertia of other rotating components in an elevator such as rotor, brake drum, shafts and coupling from the above value of  $I_1$  and get the moment of inertia of flywheel ( $I_s$ ). The flywheel's mass can also be determined from the following formula:

$$I_s = \int \rho x^2 dm$$

where  $\rho$  = distance between the mass elements of flywheel and the axis of rotation (variable)

Since the method of determine the angular acceleration is already determined, the actual braking torque can be experimentally calculated with data collected for braking time  $t_b$

$$M_b = \frac{\Pi \times n_2 \times I_1}{30 t_b}$$

The selection and testing of the braking system are probably the most important steps during an elevator design, requiring meticulous carefulness and consideration of safety regulations for the concerned location. The brake should be simple, reliable and easily accessible for maintenance and inspection. The control unit associated with it should also be setup properly to control the braking system in multiple conditions such as:

- a. If the car starts to move even though no travel command was given, brake should be applied.

- b. If overspeed takes place, the brake should be applied.
- c. If the car fails to move after giving travel command, brake should be applied to allow for inspection of the cause.
- d. If power failure or an elevator malfunction occurs, the brake should be applied to stop and hold the car in its position [1].

### *2.3. Safety Gear*

For any good engineering design from safety perspective, a redundancy should be built in for fail-safe. Almost all locations around the world have safety regulations requiring elevators with wire ropes or chains suspension to consist of a safety gear. Safety gears are used as a fail-safe to stop the car and/or counterweight and are located below them (could have additional safety gears at other locations as well). The ASME Safety Code for elevators implemented in most states require a safety gear for counterweights when occupied spaces are situated under the elevator well [12].

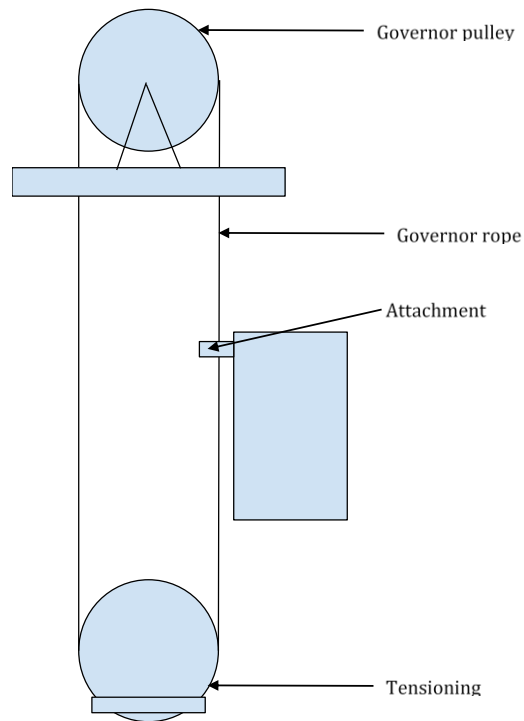
Whenever a car's speed in downward direction is greater than a certain predetermined value, the safety gear grips the guide rails and stops the car. The reason behind the car's increase of speed could be anything, for example - snapped wire ropes/chains or failed suspension, and should not matter when it comes to the operation of safety gears.

Safety gears may or may not incorporate an elastic buffer or energy dissipation system. Its requirements are based on the rated speed of the elevator. For United States, the following regulations should be considered when choosing the type of safety gear [12].

1. If the rated speed is less than 0.76 m/s, the safety gear does not need to have a flexible medium to limit the pressure on guide rails. This is also known as instantaneous type safety gear.
2. If the rated speed is up to 2.5 m/s, safety gears may be instantaneous type with buffered effect. The buffer may be elastic system that dissipates energy or accumulates energy with buffered return movement. Commonly, oil buffers are placed between lower part of the car frame and a safety plank placed on guide rails.
3. For rated speeds over 2.5 m/s or any duplex safety gears, progressive type safety gears must be installed that limits the retarding force.

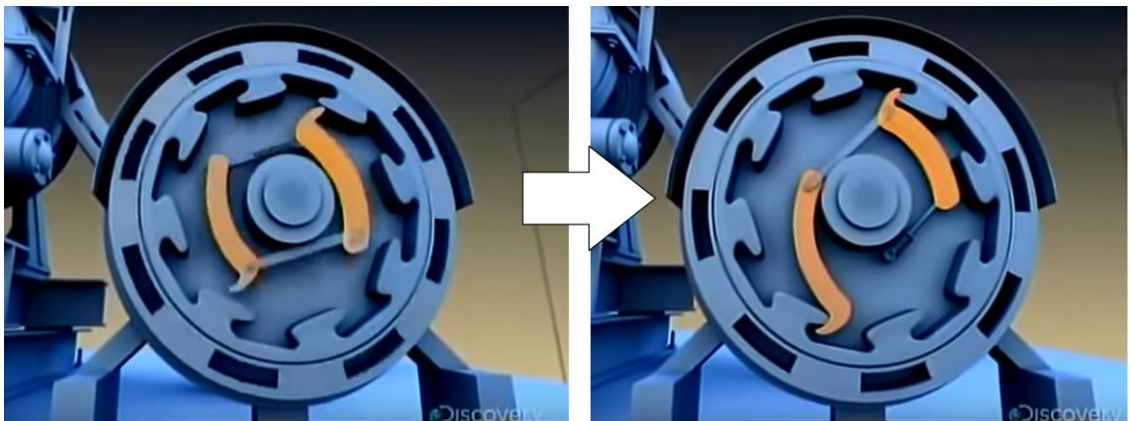
Safety gears work in combination with overspeed governor and an overspeed switch. The overspeed switch is mounted on the overspeed governor and initiates the operation of safety gears.

Safety gears could be designed in a few different ways but all of them involve grabbing and holding the elevator car in its place when the governor detects overspeed. A common design is shown in Figure 13 where the governor rope is looped around the shown governor sheave located at the top of the elevator hoistway. The flyweights in the middle are normally rotating in position with the help of a high-tension spring. When the elevator car speeds up, so does the rope attached to this sheave, and the centrifugal force pushes the flywheel outwards to lock into the ratchets which results in the stopping of the governor [14].



*Figure 12: Overspeed Governor System Arrangement [1]*

**Adapted from:** L. Janovsky, *Elevator Mechanical Design*, 2nd ed., p. 209, Ellis Horwood Limited, 1993.



*Figure 13: Overspeed Governor before and after locking [14]*

**Adapted from:** S. Crosloy, *How Elevator Works*, Youtube, 11 Aug 2015, Available: [https://www.youtube.com/watch?v=u-DI7GXyb\\_4&t=303s](https://www.youtube.com/watch?v=u-DI7GXyb_4&t=303s), Accessed 15 March 2019.



When the flywheels in the overspeed governor is locked, this action pulls the levers on the safety gears (Figure 14) attached to the elevator car which are designed to grip into the guide rails with enough deceleration to stop the car during emergency, but not too abruptly that the passengers inside may get hurt [1].



*Figure 14: A typical elevator Safety Gear [31]*

**Source(s):** Shanghai KISA Industry Co. Ltd., *Elevator Progressive Safety Gear OX-188A*, [Online] Available: <http://www.kisa-global.com/elevator-safety-devices/elevator-safety-gear/elevator-progressive-safety-gear-ox-188a.html>, Accessed 17 February 2019.

### **3. SAFETY**

Even with this brief introduction to elevators, it is clear that elevator design and manufacturing is a complicated process that involves the assembly of several components that are engineered to work together. The manufacturing plant for ThyssenKrupp Elevator Americas located in Middleton, Tennessee has separate departments for sheet metals, fabrication, signals, traction controls, safety gears, machining, doors, packaging, etc. that manufactures all the required elevator parts, most of which are assembled together at the installation location only.

Elevators have a very important role, not only in skyscrapers and large buildings, but also in public transportation where they are used to move passengers vertically to and from different grade levels. Keeping the elevator operational is critical, especially for people with disabilities who rely on elevators for their transportation needs and are inconvenienced the most when elevators break down.

Safety, in general, is a very critical branch of engineering which should be taken in consideration when designing any product. There are several bodies such as American Society of Mechanical Engineers (ASME), Occupational Safety and Health Administration (OSHA), American with Disabilities Act (ADA), etc. that enforce codes

and regulations to ensure any engineered goods are safe, accessible and unbiased for all consumers. ASME's Standard A17.1 Safety Code for Elevators and Escalators is the standard document that most agencies are required to follow along with local or state building codes, HVAC codes, National Fire Protection Association standards for electrical, fire sprinklers, fire alarms and plumbing codes, and state and federal civil rights legislation for accessibility. An equipment that is not properly maintained over longer period could result in severe accidents and even injuries and fatalities. Just as a faulty design of a bridge puts into risk the hundreds of people that travel over or under the bridge, which could result in a disaster, in case of elevators, an elevator malfunction puts into risk its passengers. People with disabilities could be inconvenienced greatly in case of malfunction, and therefore, ADA enforces regulations to make sure they are maintained and repaired promptly [16]. The importance of safety in engineering cannot be overstated. According to Consumer Watch, about 900,000 elevators serve about 18 billion passenger trips every year in the United States [15]. For an equipment that is used so frequently on a day to day basis, the importance of safety is even more critical.

However, elevators, in general, are not the primary focus for most agencies since it is not a source of income for the agencies that own and run it. A residential complex is focused on making money through its renters, not by operating its elevators. Elevators used in public transportation such as railway transits are there for convenience and efficiency, and are an expense rather than a source of income. Therefore, despite its importance, elevators are often overlooked. Most of these agencies do not keep spare replacement parts for the elevator(s). The prompt repairs required by the ADA is not very effectively

implemented. Most agencies lack proper asset management to perform maintenance and repairs in time, and very few actually keep proper documentation for these tasks.

As in any engineering design, redundancies are an important part of designing an elevator system. Along with brakes, safety gears as fail-safe are integrated into the design of an elevator. Even though one suspension rope is technically deemed sufficient, multiple cables are used as back-up. In case of power outage or unexpected power loss, an elevator should be able to brake safely. Due to modern advances in technology, elevators are generally very safe from a technical standpoint. The negligence in maintenance and managements are usually at fault for most elevator related accidents.

To understand the current safety practices in modern elevator systems, case studies of past elevator related accidents and current maintenance practices can be useful.

### *3.1 Elevator Related Accidents in the Past*

Modern elevator systems have reliable braking systems with fail-safe mechanisms due to which elevators are considered very safe in general. According to Consumer Watch, there are approximately 900,000 elevators in the United States that serve an average of 20,000 people per year, resulting in about 18 billion passenger trips annually [15]. According to United States Bureau of Labor Statistics and Consumer Product Safety, elevators related accidents kill about 27 people and seriously injure about 10,200 people every year in the United States [15]. Considering the frequency of elevator use, it can be seen that the

accidents occur very rarely, but they do occur regardless. Table 1 lists and compares different types of elevator related accidents over the last few decades.

*Table 1: Case Study of Elevator Related Accidents in the Past*

Date	Description	Location	Elevator Plunge? (Y/N)	No. of Passengers	Fatalities	Injuries	Root Cause
11/16/2018	Elevator car plunged 84 floors from 95th floor to 11th floor. Elevator had passed Annual Safety Inspection in July [17, 18]	Former John Hancock Center, Chicago	Y (did not hit the ground; stopped at 11th floor)	6	0	0	One of the suspension cables snapped
08/16/2003	Passenger was trapped by elevator doors when trying to get in. The elevator rose upwards (without doors closed) decapitating the trapped passenger [19]	Christus St. Joseph Hospital, Houston, TX	N	2	1	0	Faulty electrical wiring on the controller resulting in malfunctioning sensors
10/15/1999	Passenger trapped in an elevator for 41 hours when the elevator stopped dead after a brief power dip. Alarms, surveillance video and all other attempts to call for help went unnoticed for 41 hours [20]	Former McGraw-Hill building, Sixth Avenue, New York	N	1	0	0	Unknown

09/24/1996	Hydraulic elevator, being worked on from below and held by two wooden poles leaning against guide rails, fell, killing the elevator construction foreman and injuring his helper [21]	Maryland	Y	N/A	1	1	The poles were not tied in place with the car, and got knocked out when the car fell due to sudden loss of hydraulic pressure
05/25/1995	Construction worker fell 33 feet while constructing an elevator shaft [22]	Nebraska	N	N/A	1	0	One of the boards used for work platform broke when the victim stepped on it
04/05/1994	Elevator Service Technician was crushed by the counter-weight while repairing elevator [23]	California	N	N/A	1	0	Technician directly in the path of descending counterweight (lack of separating rigid screen between the technician and counterweight)

The six sample accident reports show six different but common types of elevator related accidents. On modern elevators, elevator plunges are very rare, unlike what is shown in movies and television. In the first case of cables snapping at the former John Hancock Center in Chicago, the safety gear stopped the car at the eleventh floor and prevented the car from abruptly stopping or crashing on the ground. There were no casualties, but it should still be considered an accident since the fail-safe mechanism worked only after the car plunged down 84 floors.

There are only two other notable incidents involving free fall of elevator car due to breakage of suspension cables in modern roped elevators, and both of them happened in

the exact same way. In 1945, a B-25 bomber pilot crashed into the 79th floor of Empire State Building due to poor visibility in fog and snapped the hoist and safety cables of two elevators. The second incident happened on September 11, 2001 in an act of terrorism when two airlines crashed into the World Trade Center Buildings (which had a total of 198 elevators), severely snapping the cables of many elevators. Both incidents involved fire due to jet fuel and several fatalities and injuries [24].

Most elevator related deaths involve workers that are working on or near an elevator, and the most common cause is death by fall into the hoistway. Other common causes of elevator related casualties involve getting caught in or between moving bodies, being struck by object such as the counterweight, collapse, etc. The following Table 2 and Figures 15-17 summarize the available data on the deaths of workers and passengers due to elevator related incidents, and while some of this data may be outdated, it still provides an idea of most common types and causes.

*Table 2: Average annual elevator related deaths by passenger type (1992 - 2009) [23]*

	Average Annual Elevator Related Deaths
Working on or near elevator	15
Passenger while at work	5
Passenger not at work	5
Total	25

**Adapted from:** M. McCann, The Center For Construction Research and Training, *Deaths and Injuries Involving Elevators and Escalators*, [Online], September 2013, Available:  
[www.cpwr.com/sites/default/files/publications/elevator\\_escalator\\_BLSapproved\\_2.pdf](http://www.cpwr.com/sites/default/files/publications/elevator_escalator_BLSapproved_2.pdf),  
 Accessed: 17 March 2019.

### Deaths related to work on or near elevators by cause (1992-2009)

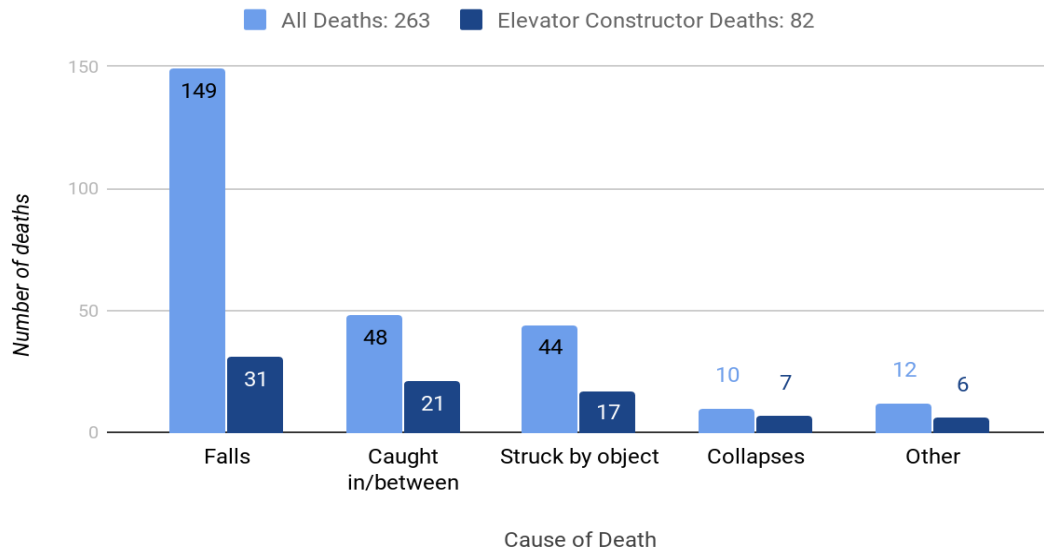


Figure 15: Deaths related to work on or near elevators by cause (1992-2009) [23]

### Elevator passenger deaths while at work, by cause (1992-2009)

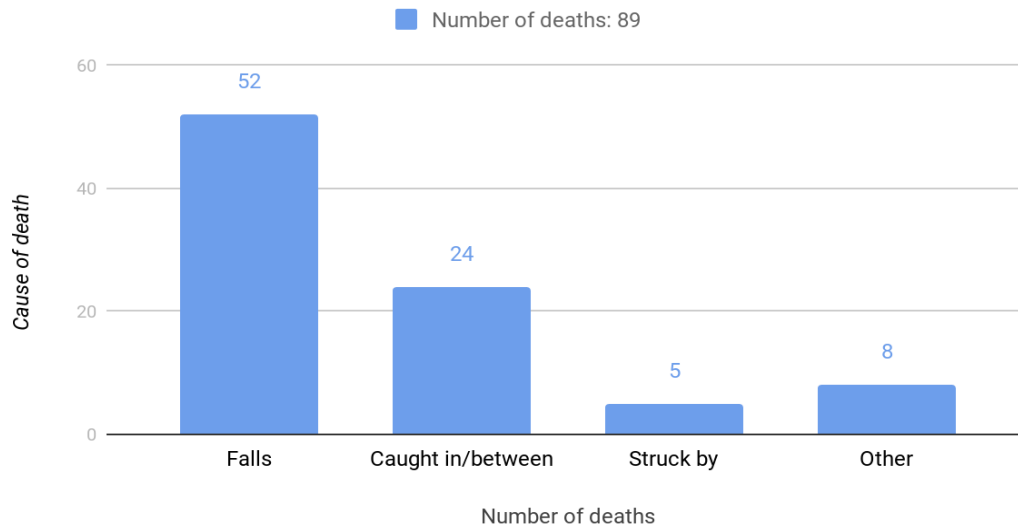
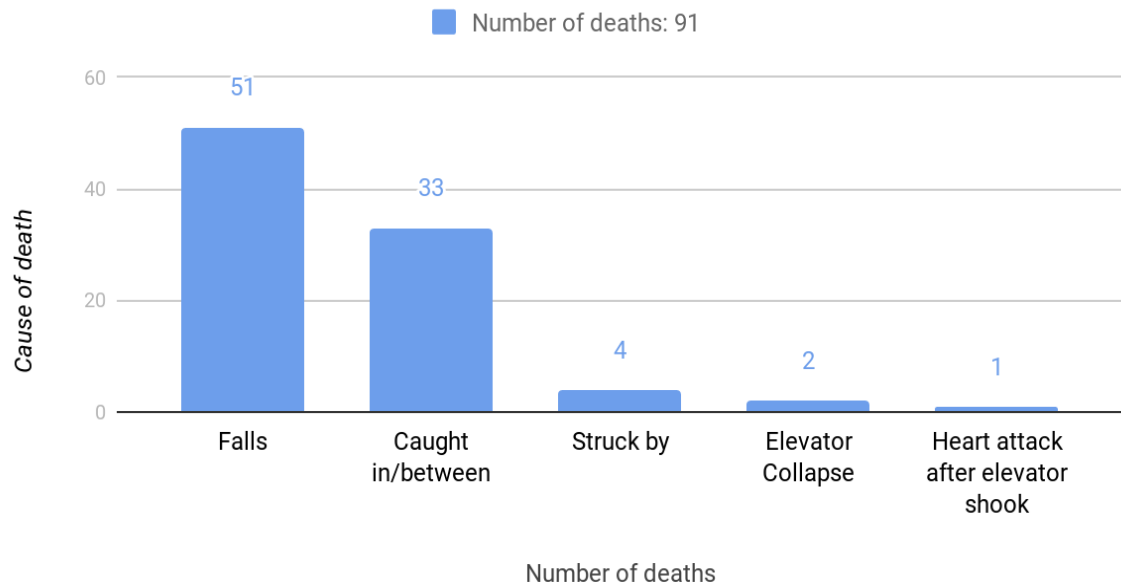


Figure 16: Elevators passengers' deaths while at work, by cause (1992 - 2009) [23]

**Adapted from** (Fig 15 and 16): M. McCann, The Center For Construction Research and Training, *Deaths and Injuries Involving Elevators and Escalators*, [Online], September 2013, Available: [www.cpwr.com/sites/default/files/publications/elevator\\_escalator\\_BLSapproved\\_2.pdf](http://www.cpwr.com/sites/default/files/publications/elevator_escalator_BLSapproved_2.pdf), Accessed: 17 March 2019.



## Elevator passengers death while not at work, by cause (1997 - 06/2010)



*Figure 17: Elevator passengers' death while at work, by cause (1992 - June 2010) [23]*

**Adapted from:** M. McCann, The Center For Construction Research and Training, *Deaths and Injuries Involving Elevators and Escalators*, [Online], September 2013, Available: [www.cpwr.com/sites/default/files/publications/elevator\\_escalator\\_BLSapproved\\_2.pdf](http://www.cpwr.com/sites/default/files/publications/elevator_escalator_BLSapproved_2.pdf), Accessed: 17 March 2019.

It can be concluded from the trend seen in Figure 15 - 17 that the most common cause of deaths in elevator related incidents is falls, followed by getting caught in or between elevator and the shaft. It can also be noticed that most casualties have happened to workers such as elevator installers, technicians and repairers.

### *3.2 Elevator Maintenance*

It is important for an elevator to be well designed for safety, but just as important is to maintain it over time. Due to aging equipment, harsh environments, extended use, customer abuse and several other factors, elevators need to be maintained in regular intervals to keep it operational and safe. Elevator maintenance is a highly specialized field and requires skilled workers to maintain, repair and replace all the elevator components in proper time intervals. It is also important for the agencies that own or operate elevators to maintain elevator parts and inventory to improve reliability and availability. Elevator manufacturers develop newer designs over time, but they should also maintain the production and inventory of components for old elevators that are still in operation.

A proactive preventive maintenance approach can go a long way in keeping elevators safe and elongating its life, and manufacturing practices such as Six Sigma, Lean and 5S can be of great help. Elevator equipment must be inspected, maintained and repaired regularly and inspections should be done to comply with safety codes, legal requirements and original equipment manufacturer (OEM) recommendations. Furthermore, the Americans with Disability Act (ADA) requires that individuals with disabilities should be able to access and use elevators readily, and they should be repaired promptly in case of damage or disorder (37.161 Maintenance of Accessible Features).<sup>[16]</sup> Likewise, the ASME A17 Safety Code for Elevators and Escalators has several requirements, some of which include: a written maintenance control program should be written for examinations, cleaning, lubrication, testing and adjustments at prescribed intervals of

time (Part 8.6.1.2), a detailed records of inspection, repairs and callbacks should be kept (Part 8.6.1.4), etc [12].

If the previous section on elevator related accidents is properly examined, it can be seen that most of them may have been avoided with proper maintenance and inspection. A well organized and comprehensive work instruction, if properly implemented, could have alerted several victims before the incident. In several cases, proper communication protocols to inform customers about a malfunctioning elevator could have prevented them from using it. Therefore, the significance of proper elevator maintenance and inspection protocols and practices cannot be overlooked.

### 3.2.1 Case Study of Elevator Maintenance and Safety Practices at MARTA

As of 2012, the Metropolitan Atlanta Rapid Transit Authority (MARTA) has 109 operational elevators throughout its railway stations in greater Atlanta, Georgia area that runs 22 hours every day with over 63 million passenger trips every year [25]. Since the elevators in such railway transit systems usually have a harsher operating condition than typical building applications, require continuous use and prompt repairs in case of damage, and maintain a large number of elevators throughout various stations, they make an ideal candidate for studying maintenance and safety practices concerning elevators. MARTA was chosen at random from one of the major transit systems to understand the current status of maintenance and safety practices.

MARTA has about 10 traction elevators and 99 hydraulic elevators, most of which were installed over 30 years ago by 10 different manufacturers [25]. Unlike most other transit systems in the country, all of MARTA's maintenance is contracted out. After a case-study on MARTA that includes a survey and phone interviews conducted by Transportation Research Board of National Academies along with other literature review, the following information was collected [25].

1. MARTA has four Qualified Elevator Inspectors (QEI) to look over the work done by outside contractors and ensure that all ASME and local safety code requirements are met through periodic inspections, random assessments, video recording reviews, etc.
2. MARTA recently transitioned from a spreadsheet program to an electronic data tracker to track elevator equipment availability with inventory monitoring and reporting capability.
3. MARTA believes that the number one cause of elevator being out of order is the equipment age resulting in increased maintenance and failures.
4. MARTA classifies its elevators as either 'special' or 'critical'. Special elevators must be repaired immediately while critical elevators can be repaired the following day after approval.
5. In order to comply with ADA requirements, when an elevator is out of order, MARTA provides buses with wheelchair lift or ramp to transport passengers with disabilities.
6. In order to communicate with customers about elevators being out of orders and educating them about proper elevator usage, MARTA utilizes its public address

(PA) announcement systems, website and scrolling message boards. MARTA also accepts customer complaints, comments and suggestions through regularly scheduled meetings, Facebook, Twitter, MARTA's website and customer service hotline.

7. The maintenance contractor (Schindler) has assigned 21 workers for Preventive Maintenance (PM) and inspections, 2 workers for quality assurance (QA) oversight, one superintendent and 21 repair technicians to service a total of 258 elevators and escalators throughout all of its stations.
8. The contractor staffs work in two rotating schedules for 12 hours coverage from 6 am to 6 pm Monday through Friday and provides a 90 minutes response time for all repairs needed 24 hours, 7 days a week. Maintenance is scheduled outside peak service hours.
9. MARTA's contract with its contractor is performance based and does not specify any training needs. However, technicians are required to have training by the contractor to maintain their Georgia state license.
10. MARTA requires from its contractor to have a written and documented maintenance program that follows OEM recommendations, ASME codes and all local requirements. The contractor is also required to maintain an inventory for spare parts. MARTA uses a maintenance management system program that utilizes an Oracle database program called FASuites.
11. MARTA requires its contractor to have scheduled preventive maintenance at specified intervals and distinguishes between scheduled versus unscheduled maintenance (unexpected repairs).

12. MARTA claims that nuisance caused by abuse of equipment and frivolous claims is a major problem that takes up valuable maintenance time [25].

### *3.3 Recommended Safety Practices*

The most common causes of elevator related accidents have been identified as: fall into the shafts, malfunction of elevator doors, stopped or stuck elevators and misalignment of elevator car with the floor (resulting in passengers getting trapped, tripping or falling).

There could be several factors involved in each particular accident, but they can be broadly identified as: poorly maintained systems, passenger safety vulnerabilities, lack of comprehensive written instructions for technicians, negligence while working on or near elevators and lack of proper communication channels.

In order to avoid such accidents as well as maintain safety in modern elevator systems more efficiently, the following safety practices are recommended.

1. Prioritize safety: Every agency should have safety as their number one priority and should consider safety practices in early stages of every project. Employee safety should be thoroughly addressed in the planning phase of all projects. Every agency should have certified inspectors, scheduled preventive maintenance procedures and safety meetings. Adequate and proactive maintenance and inspections should be done, tracked and documented on elevator equipment on regular intervals.

2. Adequate Fall Protection: Since falls are the most common cause of fatalities, adequate fall protection should be ensured in elevator shafts that may involve utilizing guide rails, scaffolding, signage and fall protection equipment. OSHA construction standard 29 CFR 1926.500-503 and the Code of Federal Regulations section 29 CFR 1910.22(b) include fall hazard regulations, that should be properly followed [3]. The walking or working surfaces should have adequate strength and structural integrity, and any holes should be protected by covers.
3. Comprehensive Written Instructions: Since elevator constructors, repairmen and technicians have been the most common victims of elevator related accidents, it demonstrates the need for comprehensive written instructions that should be maintained, implemented and enforced for any work to be done on or near an elevator.
4. Lockout/Tagout Procedures: Despite OSHA's lockout/tagout procedures for general industry (29 CFR 1910.147), several elevator related accidents have been caused by failure to ensure stability of equipment or failure to de-energize electrical circuits, resulting in victims caught in or between elevator and shaft, struck by moving parts and some falls. Proper written safety procedures and trained personnel should be implemented to enforce the needed lockout/tagout system.

5. Elevators as Confined Spaces: Most elevator accidents occur within the hoist way, and therefore, it is important to treat the elevator shafts as confined spaces and follow the corresponding OSHA standards to take necessary precautions and use of protective emergency equipment (1926.21(b)(6)(i)) [3]. A permit requiring procedure should be implemented that prevents unauthorized access to the hoist way.
6. Training and Qualifications: Since elevator equipment require specialized attention and skills, all agencies should implement an effective training program for all its workers with labs. mock-ups, mentoring, hands-on exposure and comprehensive training materials. Concerned parties should be made aware of all the relevant safety codes and legal requirements. Only qualified personnel should be allowed to work on or near elevators, and special focus should be placed on recognition and control of hazards. The effectiveness of the training should also be analyzed with time and updated if needed.
7. Asset Management: Since elevators are usually not a source of income and most agencies face budget issues, asset management from the initial stages is very critical. Assessments should be done with all relevant considerations to ensure energy savings, proper budgeting (doing more with reduced budgets), minimize unexpected damages and repairs, and prolongation of equipment life.



8. **Equipment Specifications:** The crafting and maintaining of technical specification that meets the needs of the elevator and establishes standards for the design, manufacture, operation and maintenance of elevators is crucial for the safe and reliable elevator service. This also helps to meet the safety codes and legal requirements, while assisting in saving energy and life-cycle costs. For instance, the rated load of an elevator should be chosen only after making an educated estimation about passenger traffic. Likewise, the requirements and effectiveness of phones, cameras, emergency buttons, displays, etc. should also be considered to ensure disaster control.
9. **Availability:** In order to ensure accessibility, safety and fulfilment of ADA requirements, all agencies should make sure that elevators or its alternatives are available to accommodate people with disabilities. Anytime an equipment is not available for customer use, it is considered to be down. Technicians should be available on-call at all times in case prompt repair is required. A proper data management system should be used to track availability in buildings or agencies that control a large number of elevators.
10. **Communication and Awareness:** It is very important to keep the public safe and informed about elevators. Many accidents can be avoided by making sure passengers are aware of any malfunction in elevators and ensuring that caution signs are not missing. In public places, service announcements and board signs should be implemented promptly and effectively. It is also important to educate

people about safe usage of elevators. There should be a properly functioning system in place to make sure that any trapped passenger can always quickly contact emergency services.

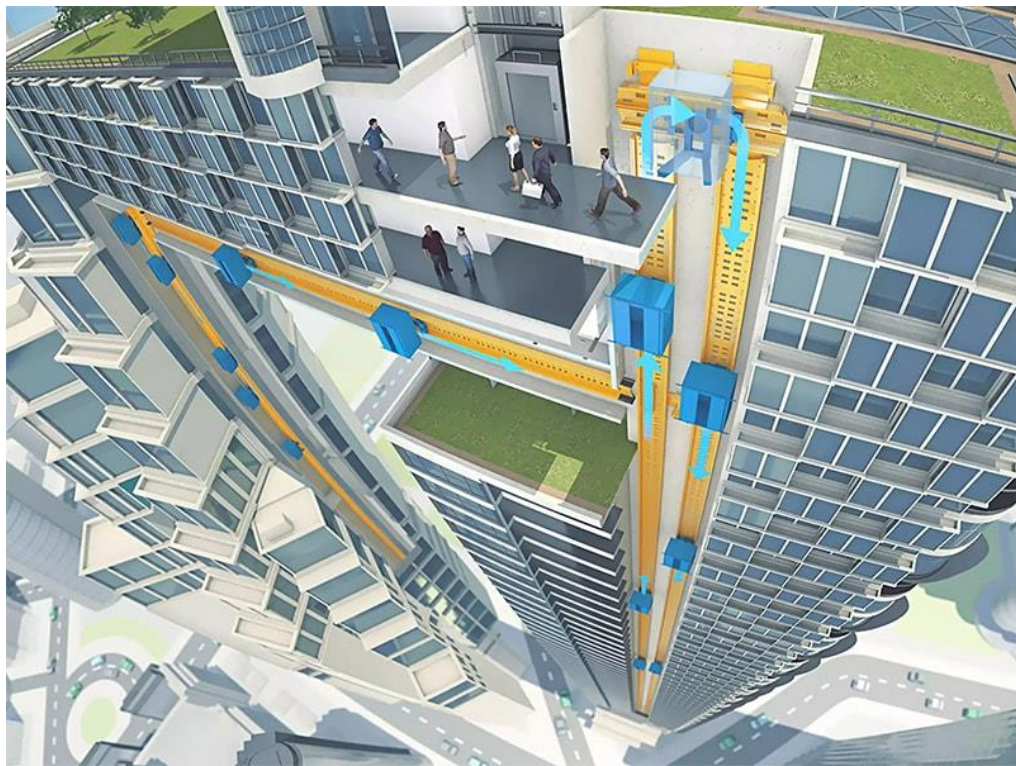
11. Modernization: Aging elevators result in increased failures, higher maintenance requirements, difficulty in finding parts, higher operating costs and increased risk of accidents. That is why, modernization of elevators should be considered whenever possible. Many elevator manufacturers provide a free modernization evaluation to determine the needs of an elevator. The evaluation includes a study of the frequency of use and shut-downs, energy costs, obsolete equipment(s) if any, worn out or outdated parts as well as decor, unsatisfied tenants, etc. and recommendations may include a transition to modern technologies such as AC gearless motor, destination dispatch systems, AC digital drive, regenerative drive, modern roller guides, digital door operators and newer cab interiors. Modernization of an elevator may help in energy saving, increasing performance, decreasing carbon footprint, reducing trip times, increasing elevator's handling performance and improving ride quality.

## **4. THE FUTURE OF ELEVATORS**

There have been several attempts and concepts of ropeless elevators in the last couple decades. Mitsubishi Electric Corporation proposed a ropeless Linear Induction motor drive elevator which would be self-propelled and can integrate multiple cars in a single hoistway.<sup>[1]</sup> The most recent work in similar technology is MULTI by ThyssenKrupp Elevators. A prototype of MUTLI has been built and tested at a test tower in Germany, and a German developer, OVG Real Estate, has placed the first commercial order for its East Side Tower Building in Berlin [26]. MULTI integrates a linear motor technology that moves multiple elevators cars in a single shaft both vertically and horizontally using modular exchangers that enables exchange between shafts and circulation of cars [2].

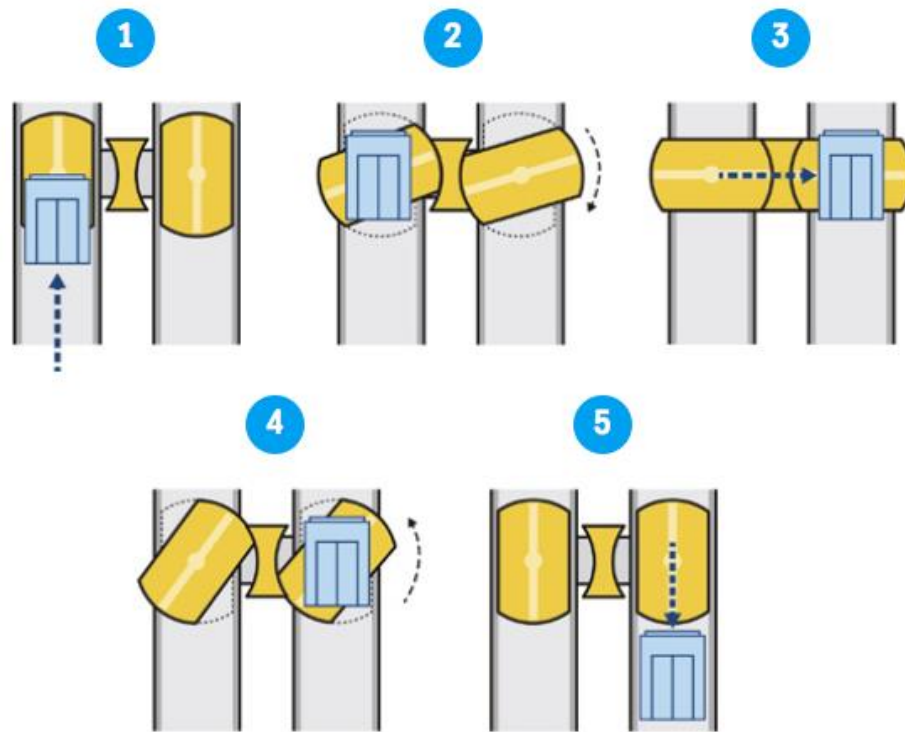
The shafts of MULTI have coils embedded to create electromagnetic field through which the cabins are guided with the help of linear induction motors. Exchangers are placed throughout the shaft which rotate enabling the cabin to move sideways if desired. This eliminates the need of suspension cables along with their disadvantages. Multiple cabins can also be used in the same shaft. This substantially increases the maglev elevators' flexibility, building's transportation capacity and efficiency, and helps to save valuable space in the buildings' architecture [2].

The concept of ropeless elevator using magnetic levitation is often considered the future of transportation inside tall and high-traffic skyscrapers. ThyssenKrupp claims that by using multiple cars in a single shaft, the wait times can be reduced to about 15 to 30 seconds only in high-rise buildings [2]. Since fewer shafts are required, the elevators' footprints is also reduced. MULTI can also increase the building's usable space by up to 25 percent, and reduces the strain on architects to design shaft alignment and height since round and complex structures can be utilized. MULTI requires lower peak power and during off-peak hours, unused cars can simply be parked without utilizing any power [2].



*Figure 18: Schematic illustration of cable-free MULTI elevator system [2]*

**Source(s):** Thyssenkrupp Elevator AG, *MULTI*, [Online], Available: <https://multi.thyssenkrupp-elevator.com/>, Accessed: 15 March 2019.



*Figure 19: Schematic of exchangers rotating in a MULTI elevator system [2]*

**Source(s):** Thyssenkrupp Elevator AG, *MULTI*, [Online], Available: <https://multi.thyssenkrupp-elevator.com/>, Accessed: 15 March 2019.

According to Thyssenkrupp, MULTI eliminates the safety hazards associated with traditional cables and makes it much safer. Multiple elevator cars moving in multiple directions in same and/or perpendicular shafts can sound dangerous, but a software is used for the cabin's multi-propulsion system to ensure no diversions from predetermined journeys. The space between cabins is also monitored by the software which ensures that in an unlikely event of two cabins getting too close, they are stopped at a safe distance apart. The emergency brakes work on a different system using batteries to stop the elevators in case of power outages. Due to the nature of linear motors, the elevator cars

cannot move if there is no power provided, which not only helps in energy saving by allowing cabin parking when not in use, but also eliminates the risk of free fall.

This advancement in technology expands several design possibilities and is undoubtedly the future of elevators. As hotels, airports, shopping malls and skyscrapers expand to become mini-cities of their own, a technology like MULTI could be the heart of transportation within those landmarks. Even the traction elevators that are currently in use in high-rise buildings have a height limit before the weight of the cables itself makes it inconvenient. A ropeless elevator system can make buildings taller, and multiple cabin/shaft system can help people get to top floors without stopping at a dozen floors in between. However, there are still some major drawbacks. First, the magnetic levitation technology is very expensive to install compared to traditional elevator types.

Considering the long-term benefits and efficiency it can provide by saving energy, space and time, only high-rise buildings with big initial budget would consider MULTI currently. In case of damage, replacing parts would be very costly as well, and therefore, ThyssenKrupp must prove its claimed reliability over time. Since it is a relatively new technology, the reliability, efficiency and safety has not been demonstrated yet in the real world, and there could potentially be other yet unidentified disadvantages. It is still a question how safety regulations will adjust to fit the linear motor technology needs.

When the twin elevators were released in 2003 by ThyssenKrupp, it didn't see a market in United States until 2016 when Georgia Tech made an order after the new safety codes for integrating two cars in a single shaft were approved. Code authorities around the United States will surely follow suit considering twin's success all over the world, but it

surely takes time and careful inspection. Such will undoubtedly also be the case for a technology like MULTI.



*Figure 20: A MULTI elevator in ThyssenKrupp test tower in Germany [2]*

**Source(s):** Thyssenkrupp Elevator AG, *MULTI*, [Online], Available: <https://multi.thyssenkrupp-elevator.com/>, Accessed: 15 March 2019.

Currently, many safety codes require the drive system to be present in a separate location that can be accessed without having to get into the elevator well [1]. Since MULTI and similar linear induction motor technologies integrate a direct drive in the hoistway gap itself by utilizing magnetic levitation through linear motors, it cannot be commercialized in several states until safety codes are updated, or the technology is modified in some

way in those locations. Several locations that have not adopted the latest ASME safety codes even require that elevators be either hydraulic or traction only. For a safer and more effective urbanization and technological progress in the field of vertical transportation, it is crucial for safety codes to keep up with time and technology, while manufacturers like Thyssenkrupp must prove the reliability, safety and applicability of their new technologies.



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